Research on the Architecture and its Implementation for Instrumentation and Measurement Cloud

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Abstract—Cloud computing has brought a new method of resource utilization and management. Nowadays some researchers are working on cloud based instrumentation and measurement systems designated as Instrumentation and Measurement Clouds. However, until now, no standard definition or detailed architecture with an implemented system for IMC has been presented. This paper adopts the philosophy of cloud computing and brings forward a relatively standard definition and a novel architecture for IMC. The architecture inherits many key features of cloud computing, such as service provision on demand, scalability and so on, for remote Instrumentation and Measurement (IM) resource utilization and management. In the architecture, instruments and sensors are virtualized into abstracted resources, and commonly used IM functions are wrapped into services. Users can use these resources and services on demand remotely. Platforms implemented under such architecture can greatly reduce the investment for building IM systems, enabling remote sharing of IM resources, increasing utilization efficiency of various resources, and facilitating the processing and analysis of Big Data from instruments and sensors. Practical systems with a typical application are implemented upon the architecture. Results of the experiment show that the new architecture has achieved the function goals of IMC and demonstrates that the novel IMC architecture can provide a new effective and efficient framework for establishing IM systems.

Index Terms—Architecture, cloud computing, distributed computing, instrumentation and measurement cloud, parallel processing, power system state estimation, cloud service

1 INTRODUCTION

SINCE instrumentation and measurement (IM) technology is closely combined with information technology, development in information technology (IT) can lead to the advance of IM technology. In the early stages, computers were used to control instruments and sensors for local data acquisition and analysis. Later on, virtual instrumentation technology was developed and many of the functions that were implemented by hardware in instruments can now be achieved by computer software. With the development of networks and the internet, remote instrumentation and measurement (RIM) emerged as a new technology in IM[1]. Such RIM technology has brought lots of benefits to related areas, especially to those areas that involve large distributed systems[2]. It can greatly facilitate instrument control, data acquisition and processing. Additionally, new computing paradigms, such as grid computing, can be integrated into IM technology to further improve the ability of data processing and resource sharing and management for distributed IM systems[3]. The grid-enabled instrumentation and measurement system (GIMS) is a typical type of those systems. GIMS brings many advantages to data intensive IM applications and heterogeneous IM resource management. However, due to some limitations of grid computing, systems that integrate a grid are eventually not widely adopted in practical use.

Currently, most IM systems are built upon local architecture or traditional client/server (C/S) architecture[4]. In local IM architecture, instruments and sensors are connected directly to the computer and it is difficult to build large IM systems. As for C/S architecture, instruments and sensors simply provide remote access interfaces through gateway servers to clients. However, both of the architectures require the user to build the entire IT system and, also, to maintain all resources. Thus, there has to be a great investment in building the whole IM system and, besides, system stability, scalability and fault tolerance can be serious problems for both of the architectures. Moreover, to satisfy resource requirement for both peak and valley load, the IM system should be built according to the peak load at the very beginning and, even if the load drops, the system cannot scale down accordingly. Therefore, the utilization rate of resource in the IM system can be quite low, especially for those systems with great load dynamics. In addition to the problems mentioned above, the large amounts of data collected from various devices need much more powerful computing resource for processing and analyzing, and traditional computing

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paradigms may be incapable of dealing with such scenarios.

In recent years, the emergence of cloud computing has brought many new approaches for resource utilization and management[5]. Cloud manages all resources as a resource pool and provides those resources as online services to end users according to their demand. Such modes can greatly increase the utilization efficiency of resources and, at the same time, save the investment of users on both hardware and software IT resources[6]. Also, big data processing and analysis technologies developed along with cloud computing make data analysis much easier and faster in the IM field[7]. Motivated by these benefits, many researchers are exploring novel cloud based IM technologies to solve the problems above[8]. Until now, most of the work carried out in the interdisciplinary area of IM and cloud computing mainly focuses on the application of cloud computing in IM systems, which can only deal with a few aspects of related problems. Little research has been carried out to build novel IM modes and architectures that can inherit the essence of cloud computing for IM systems. Some literatures have brought up new concepts or terminologies such as instrumentation cloud or sensor cloud, but with only conceptual architectures. However, designing such an instrumentation and measurement cloud with detailed architecture and a corresponding practical system is very important for current IM science to face the many aforementioned challenges.

This paper introduces a novel IMC architecture with detailed system implementations. The architecture abstracts instruments and sensors into resources, and encapsulates frequently used modules and functions into services. Services are deployed in the cloud and users can consume these services on demand. IM applications are also deployed and run in the IMC platform. All IT resources are allocated and managed by the IAAS (Infrastructure as A Service) cloud platform which will reduce investments for users and also increase resource utilization efficiency. By integrating cloud computing and big data processing technologies, IMC can benefit a lot from advantages such as system scalability, fault tolerance, distributed and parallel computing, and so on. An actual system based on this architecture is implemented using various cloud computing frameworks. Applications and experiments are designed to test the system. Results show that the IMC architecture designed in this paper can properly integrate cloud computing with IM technologies and greatly facilitate the building, managing and use of IM systems and resources.

The remainder of this paper is organized as follows: section 2 presents related work; section 3 introduces key concepts of IMC; section 4 describes the detailed IMC architecture designed by this paper; section 5 illustrates the implementation of the architecture; section 6 provides some applications and tests over the IMC system; section 7 discusses challenges and limitations of IMC; and finally, section 8 concludes the whole paper.

2 Related work

Most of the work related to IMC mainly focuses on the following areas: Grid-enabled instrumentation systems (GEIS)[9], sensor clouds[10] and instrumentation clouds[11].

GEIS mainly focuses on converting instruments into grid services[12], so that heterogeneous instrumentation resources can be accessed and managed through a grid, which can facilitate data intensive applications to use various grid resources and provide distributed instrumentation and experiment collaborations over the grid[13]. In GEIS, instruments are abstracted into unified services through middleware technologies and standard models. Typical GEISs including Instrument Element[14] architecture from the GridCC project, common instrument middleware architecture[15], e-infrastructure for remote instrumentation from the DORII project[3] and virtual laboratory architecture[16].

Although GEIS provides a good way for distributed instrumentation and collaborative experiments over the grid, limitations of grid computing, such as complexity, constrained accessibility and so on, prevented it from prevailing among scientific and industrial areas. However, some of the research work, which regards the common aspects of GEIS and IMC, in GEIS can guide the study of IMC. The data retrieval and transmission approach in distributed IM systems is an important one of those aspects. Through comprehensive research, [12] and [17] demonstrated that publish/subscribe mechanisms are more efficient for real-time collecting and transmitting data in a distributed IM environment. Thus, in the work of this paper, a message-based publish/subscribe mechanism is adopted as the information and data dissemination method.

Just like IMC, the sensor cloud is also a very new concept. In [18] a sensor cloud infrastructure is developed and physical sensors are abstracted into virtual sensor objects. Such virtual sensor objects combined with related sensor definition templates can provide measurement services to end users. Besides, service and accounting models are designed, which makes the sensor cloud infrastructure conform to the philosophy of cloud computing. Another project working on cloud-based sensing systems is the S4T(Stack4Things) project[19]. This project is the base for the #SmartME[20] project which mainly focuses on morphing a city into a smart city. The S4T project is trying to build up a cloud platform for managing a large number of sensors and actuators deployed in a smart city. One of the main ideas of the S4T project is virtualizing sensors and actuators into abstract resources similar to those resources in cloud computing and providing sensing and actuating services through the S4T platform. Thus, the S4T platform is also viable for building a sensor cloud. Some other researchers also use the terminology 'sensor cloud', but most of them only concentrate on the application of cloud computing technology in sensor control and management[21],[22],[23],[24]. Sensors are much simpler than instruments, however they can also be treated as instruments, only with less functions.

Current studies of instrumentation clouds only bring forward conceptual models and architectures with few details or implementations provided[11],[25],[26]. Some other research work is mainly about applications of cloud computing in massive data storage and processing[27],[28],[29], which, as explained before, only provide solutions for a few of the problems faced by current IM systems.

Compared with the above research, the work of this paper has the following advantages: (1) the IMC platform developed in this paper is more open and easier to access than GEIS; (2) the IMC platform can manage both sensors and instruments, and provide commonly used IM functions as scalable services to end users; (3) the IMC system implemented according to the IMC architecture in this paper is a real cloud platform for the IM field, rather than just application of cloud computing technologies in the IM field. All these advantages are achieved by adopting a cloud-based resource management and usage mode, and also using state-of-the-art technologies from cloud computing and big data fields. Details will be presented in the following sections.

3 Instrumentation and Measurement Cloud

Currently, no standard definition for IMC is presented. This section brings up a relatively standard definition for IMC and its related elements by adopting key ideas of cloud computing into IM field.

3.1 Definition of IMC

The key ideas of cloud computing are: resource abstraction and virtualization, services delivered on demand, and scalability[30]. Owing to these ideas, cloud computing can provide scalable, on demand hardware and software resources remotely. As introduced in Section 1, traditional IM systems and modes do not own such advantages. To inherit these merits, it is necessary to integrate cloud computing and related big data models into the IM field, and establish a novel Instrumentation and Measurement Cloud (IMC). Based on our previous work[31], a definition for IMC is brought forward as follows:

Definition 1. *Instrumentation and Measurement Cloud(IMC) is a model, based upon cloud computing and big data frameworks, for enabling on-demand, convenient, ubiquitous network access to a shared pool of Instrumentation and Measurement(IM) resources(e.g. instruments, sensors, actuators) and services that can be rapidly provided and released with minimal interaction with resource provider and end user.*

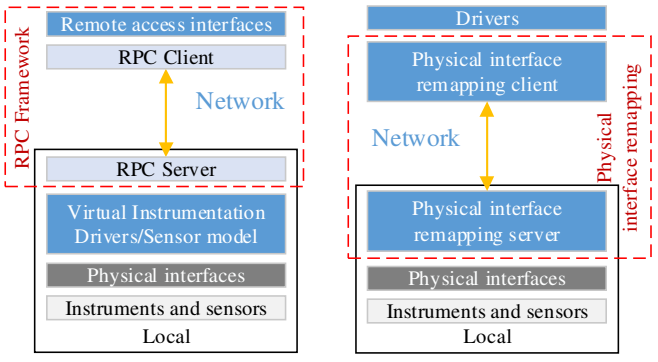
From definition 1, it can be seen that IMC contains two direct elements, resource and service, and a third hidden element which is the IM application designed by the user. To distinguish these elements from similar concepts in the traditional IM field, IMC resources, IMC services and IMC applications are used to feature these three elements of IMC. Detailed definitions of these elements will be given in the following sections. The definition of IMC also points out that IMC relies on cloud computing and big data frameworks. This is because IMC itself requires the support of cloud computing and big data frameworks to achieve many of the function requirements illustrated in the definition.

3.2 Definition of IMC resource

Definition 2. *Instrumentation and Measurement Cloud resource stands for virtualized instrument, sensor or actuator resource that is connected to IMC through network for online sharing and management.*

As can be seen from the above definition, computing resources are not included in IMC resources. The reason why it defines IMC resource this way is that computing resources, such as the CPU, storage and the network, are managed and provided by cloud computing frameworks of IMC, and, to IMC, they play the role of service. However, not all instruments, sensors and actuators can be converted to IMC resources. Some IM devices that cannot be virtualized or connected to IMC for use and management are not eligible to become IMC resources. Similar to resources in cloud computing, IMC resource can only be shared at different times and that means only one user can control the resource at the same time.

Unlike computing, storage and networking resources, instruments and sensors have heterogeneous software and hardware architecture which means it is very difficult to virtualize them into a unified resource pool and at the same time keep their full features. However, thanks to virtual instrumentation (VI) technology and standard sensor models, many of the modern instruments and sensors can provide unified access interfaces. But such interfaces are designed just for local drivers. To virtualize those IM devices into IMC resources, interface remapping through the network is required. Generally, there are two ways to remap the interfaces, as shown in Fig. 1.



(a)Software interface remapping (b)Physical interface remapping

Fig. 1. Remote instrument and sensor interface remapping

Fig. 1(a) shows a software interface remapping scheme using a remote procedure call (RPC). Such a scheme is more data-oriented, since it mainly focuses on manipulating data exchanged between physical devices and up-level applications. This method is easier but less flexible. For different VI frameworks or sensor models, corresponding RPC modules should be developed.

The second method, illustrated in Fig. 1(b), remotely

maps physical interfaces, such as USB[32], RS-232, GPIB and many others, to the cloud side, thus IM device connections to those interfaces will be forwarded to the cloud. Physical interface remapping is a device-oriented design is more concerned about the device itself rather than the data generated from the device. It actually remaps devices to remote servers or applications and, thus, supports full features of the device. However, implementation of this method is much more difficult, especially for high speed interfaces such as PCIE, than that of the software interface remapping approach. And also, this method only supports VM (Virtual Machine) based applications, which means each IMC resource should be attached to a VM in the cloud. An IM system based on physical interface remapping is more like a traditional IM system and the only difference is that the system is deployed in the cloud. Unless there are special requirements, it is better to use software interface remapping for IM device virtualization.

3.3 Definition of IMC service

Definition 3. *Instrumentation and Measurement Cloud service stands for online, scalable, shared IM function, cloud computing resource service or big data processing service that can be consumed through IMC by IMC applications on demand.*

The IMC service is closer to the concept of SAAS (Software as a Service) in cloud computing[33]. Traditionally, commonly-used IM functions are provided through commercial software packages and users have to purchase the packages, and install and run them locally. However, in IMC, commonly-used IM functions are encapsulated into online services. Users can consume those services on demand and all those services are running in IMC. In this way, much of the computation load can be shifted to the cloud side which will reduce the requirements for computing resources on the user side. When consuming IMC services, users just need to send data to input interfaces of IMC services and retrieve results from output interfaces. Fig. 2 shows the detailed service mode of IMC services.

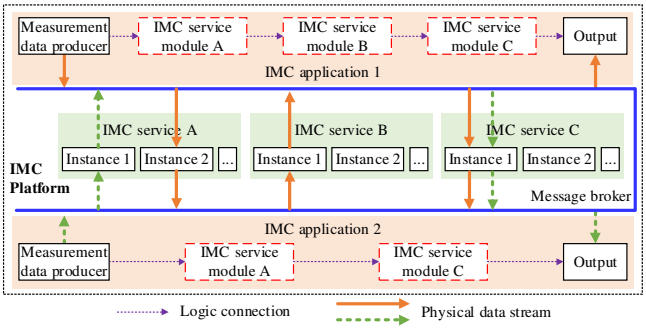


Fig. 2 Service mode of IMC services

Fig. 2 presents service mode of IMC services for real-time IM stream data processing. Here, real-time means data are processed as soon as they are received, as distinguished from batch processing. Since data from virtualized IM resources are normally stream data, they should be processed in time before storing to databases or files.

In Fig. 2, there are three IMC services which implement three commonly used IM functions, e.g. calculation of electrical power and so on, respectively. Two IMC applications are consuming these IMC services to carry out some IM tasks. The IMC application represents application that consumes both IMC services and IMC resources, and carries out user defined custom logic to fulfill specific IM tasks. A detailed definition of the IMC application will be given in the following section. When consuming IMC services, IMC service modules in IMC applications are just logical representations of IMC service instances that carry out actual data processing procedures. For example, in Fig. 2, IMC service modules A, B and C in both IMC applications 1 and 2 are just used to represent logical data process flows. When IMC applications are running, data acquired from IMC resources are not sent to IMC service modules for processing. Instead, data are sent to running IMC service instances in IMC through an information dissemination system, such as message broker, for processing. In this way, data processing is carried out in IMC service instances, not in IMC applications.

Each IMC service can run multiple instances and each instance can serve multiple IMC applications. By implementing IMC services in cloud computing and big data frameworks, IMC services can inherit advantages, such as distribute parallel processing, fault tolerance, scalability, load balancing, dynamic load transfer and so on, from those frameworks.

3.4 Definition of IMC application

Definition 3. *Instrumentation and Measurement Cloud application is the application program that consumes IMC resources and IMC services, and carries out custom logics to fulfill user defined IM tasks.*

Although the IMC platform can provide remote access to IMC services and IMC resources, it still requires the user to organize those services and manipulate those resources to carry out specific IM tasks. Since most of the computation intensive data processing procedures can be implemented into IMC services deployed in IMC platforms, IMC applications are normally light-weighted. By developing web-based online IDE (Integrated Development Environment), IMC can provide a PAAS (Platform as a Service) service to users, so that end users can develop, deploy and run IMC applications online through a web browser. In this case, building a distributed IM system will be much easier, since all IM resources and commonly used IM functions can be obtained online through IMC.

3.5 Instrumentation and Measurement mode in IMC

The instrumentation and measurement mode in IMC can be depicted as in Fig. 3.

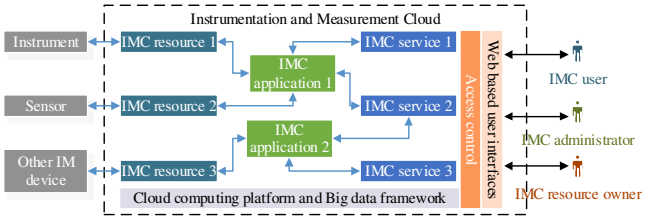


Fig. 3 Instrumentation and measurement mode in IMC

In Fig. 3, there is an IMC user, IMC administrator and IMC resource owner. The IMC user normally consumes IMC resources and IMC services, and develops IMC applications to carry out IM tasks. The IMC administrator is responsible for building and maintaining the IMC platform. All IMC resources are provided and maintained by IMC resource owners. While the IMC service can be developed by any of them, it is the IMC administrator's responsibility to check the quality of the service and decide whether to deploy it or not. As shown in Fig. 3, with a web-based user interface and access control, IMC users can request IMC resources and IMC services, and develop IMC applications online. By deploying IMC applications in the IMC platform, IMC users no longer need to invest in, establish and maintain the whole ICT (Information and Communication Technology) system for their IM tasks. Instead, they can use resources and services provided by the IMC platform according to their need.

The above definitions have clarified the basic function requirements and characteristics of IMC. Although technologies from IM science, cloud computing and big data fields provide full support for the above function requirements, there was no detailed architecture to integrate all these technologies and guide the implementation of the IMC platform. In the following section, a novel IMC architecture, which owns the above important characteristics, will be presented.

4 Novel Architecture for Instrumentation and Measurement Cloud

The overall IMC architecture developed in this paper is shown in Fig 4. This architecture mainly consists of six parts, which are the coordination system, message broker, IMC resource agent, IMC service pool, IMC application executor and IMC manager. Details of each part will be presented in the following sections.

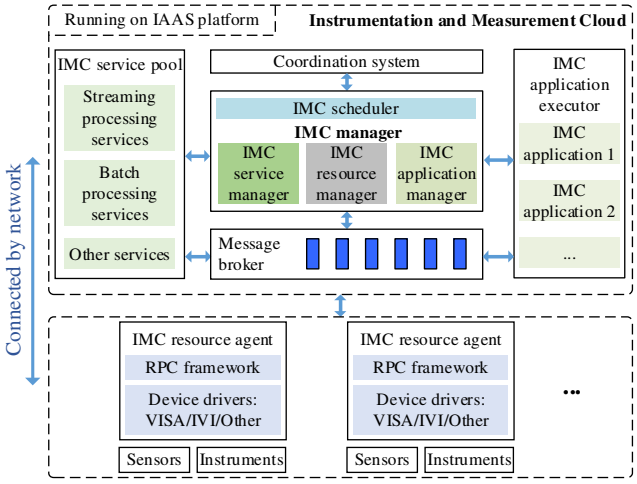


Fig. 4 Novel architecture for IMC

4.1 Coordination system and Message broker

The Coordination system records all configuration data and management data of IMC services, IMC resources and IMC applications. As the IMC architecture in Fig. 4 is distributed, the coordination system should have a distributed syncronization mechanism for data manipulation. The coordination system should also support event notification, so that events from the three IMC elements can be discovered across the architecture and corresponding actions can be taken.

The message broker is the core component for data transmission. Data exchanges between IMC applications, IMC services and IMC resources are mainly achieved by the message broker. As illustrated in section 2, the effective and efficient way to transmit data in a distributed environment is via a publish/subscribe based messaging mechanism, thus a publish/subscribe based message broker is a good choice for data transmission in IMC. And, to transmit data over the message broker, a related client of the message broker should be integrated into IMC elements.

4.2 IMC resource agent

The IMC resource agent is responsible for instrument and sensor virtualization and IM resource registration.

As illustrated in section 3.2, instruments and sensors can be virtualized through VI frameworks and standard sensor models. By virtualization, instruments and sensors are encapsulated into resources with standard access interfaces. And, assisted by RPC frameworks, these interfaces can be called remotely from IM applications in the cloud, which will bring much convenience for building distributed IM systems. Once virtualized, these IM resources can be registered into IMC by the IMC resource agent, so that users can use them over networks. To use IMC resources, users should first make a reservation for each resource through the IMC manager. After reservation, an access id with start and end time stamps will be allocated to user applications and the IMC resource agent, and also, the entry of the resource, such as the URL of the IMC resource agent, will be sent to user applications.

When user applications want to access the reserved resources, firstly they will have to send access the id to the IMC resource agent through that entry, and the IMC resource agent will then check if it also has the same access id and whether the current time is between the reserved time span. If all requirements are satisfied, the IMC resource agent will allocate a resource handler for the application and allow the application to use the resource through RPC interfaces for instrumentation and measurement tasks. The complete procedure for registering and using IMC resources in the IMC is depicted through the UML activity diagram shown in Fig. 5.

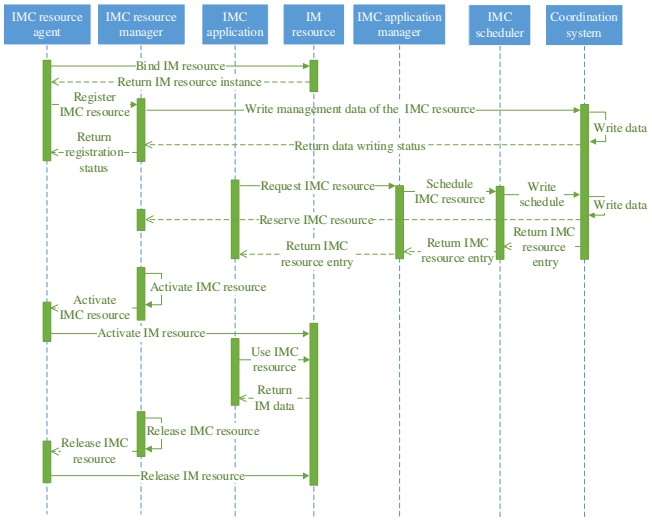


Fig. 5 Steps required for consuming IMC resources in IMC

4.3 IMC service pool

In IMC, services represent modularized function blocks implemented in big data analyzing and cloud computing frameworks. Such IMC services include stream data processing modules, batch processing modules and other function modules. IMC services are normally developed and deployed in parallel and distributed cloud computing platforms. Each type of service can serve multiple IM applications and the platform or framework running these services will provide scaling, parallel processing and fault tolerance abilities. Services and applications in IMC are connected by a publish /subscribe based message broker.

The message broker is used to transmit data between services, resources and applications. Currently, many message brokers support clustering, which means brokers can support fault tolerance. However, overheads from message headings and message routing can degrade data transmission performance. To deal with this problem, some message brokers support light message headings and a simple message routing scheme. This can increase message processing and transmission speed, but at the same time reduce flexibility and functionality of the broker. Other brokers can provide more flexible control over message transmission and fault tolerance by adding extra information to messages but this will bring more overheads. IMC service providers should choose the broker according to their needs.

All services in IMC should register themselves through the IMC manager. When registering, the IMC manager will create data entries for each IMC service in the coordination system and write management data of services into those entries. Normally, each IMC service has several input interfaces and output interfaces. For input interfaces of a service, the IMC manager will write message broker topics that they are listening on to their data entries and if IMC applications are to consume this service, they can get those topics through the IMC manager and then publish messages to those topics. To get processed data from the IMC service, IMC applications need to write topics that their sink modules are listening on to data entries of the service's output interfaces.

As for stream data processing services, each of them has several input and output interfaces. Input interfaces will listen on dedicated message topics and, as for output interfaces, they will watch on a data cache entry that stores destination message topics for outputting data.

For batch processing services, file systems and databases constitute the data sources. In most cases, batch processing is an off-line post-processing approach but IM systems normally deal with real-time stream data processing, so batch processing services will not be studied in this paper. However, batch processing services are still indispensable to the whole IMC architecture.

To enable a parallel and distribute computing paradigm and enhance the ability of fault tolerance for IMC services, three key roles should be followed when developing IMC services:

1. Reduce coupling and dependency between data. Only in this way can the service be implemented in a parallel computing paradigm.

2. Make data self-descriptive. This is very important for multiple IMC applications to share the same service instance. Since data can describe themselves, service instance does not need to know which application these data come from.

3. Try to avoid state caching for IMC applications in services and use dedicated memory cache systems. Most distributed and parallel cloud computing frameworks support fault tolerance. That means that when some processing nodes go down the system can still run in a normal state. However, if those nodes cache states of current applications they serve, all these states will be lost and restoring the service process can be difficult, especially for streaming processing applications. Moreover, avoiding state caching in service instances can facilitate online load transfer which is vital to load balancing.

4.4 IMC application executor

The IMC application executor is responsible for running IMC applications that are deployed in the IMC. It often consists of a script interpreter or runtime engine. By deploying IM applications into the IMC, users can save the trouble of maintaining the client side. With proper user interfaces, users can access their IM applications through mobile terminals.

4.5 IMC manager

The kernel of the whole architecture is the IMC manager. The IMC manager contains four main components: the resource manager, the service manager, the application manager and the scheduler. All IMC resources, related IMC services and IMC applications are registered and managed by the corresponding component of the IMC manager. Fig. 6 shows how the IMC manager works.

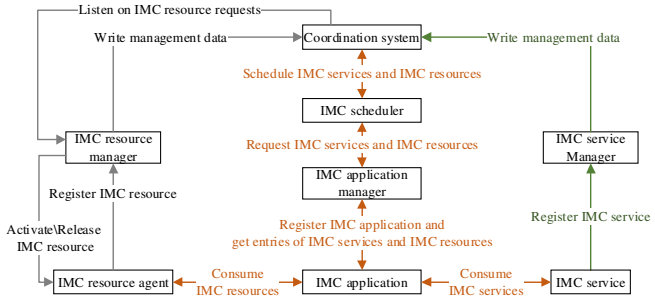


Fig. 6 Details of IMC manager

When registering resources, the resource manager will create a data entry for each resource and store their Management data（之前用的 meta data 后来全改为 management data）. Under an RPC framework, management data often contains the URL of the resource side RPC server. Another data entry that caches all reservation information of the resource is also created upon registration. Such reservation information will also be sent to the IMC resource agent for authorization purposes. A similar process happens when the service manager is registering services. However, the service manager mainly maintains management data about interfaces of each service. Service and resource requests from IMC applications are processed by the application manager. When IMC applications request services or resources, the application manager will query the coordination system, get all related management data and send these data back to applications. At the same time, some of the message broker's context of the sink module in the applications will be written into data entries that output interfaces of services are listening on.

The tasks of the scheduler are IMC resource and service scheduling, load balancing and scaling of IMC services. Fig. 7 shows how those tasks are handled by the IMC scheduler.

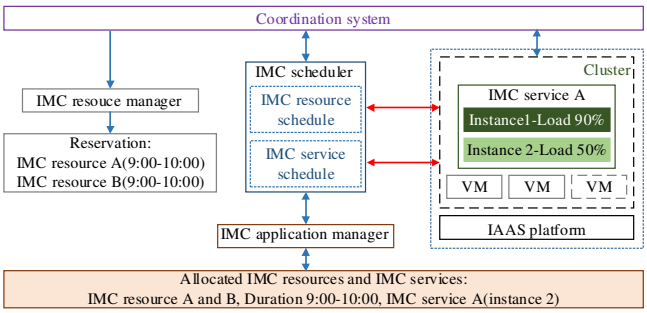


Fig. 7 Work procedure of the scheduler

As shown in Fig. 7, when an IMC application requests IMC resources, the scheduler will call related algorithms to calculate a valid time span for those resources and make reservations. Currently most IM resources are not like services, and they cannot be shared at the same time by different users. Thus, the scheduling running time of IMC resources according to users' needs is very important. Load balancing and service scaling is done by scaling the cluster that runs the service. When IMC applications request services, the scheduler will query the load capacity of each service instance and select the ones with low load capacities. Also when several service instances have low load capacities, the scheduler can transfer tasks on these instances to on instance and shut down other instances. Such online load balancing can greatly increase the utilization efficiency of computing, storage and other resources in the cloud. However, online load balancing needs the support from both the framework that runs the service and the service itself.

Whenever an IMC application is registered in the IMC, the application manager will record all consumed services and resources. If the state of any of the services or resources changes, a related event will be sent to the application manager, which will trigger the state transition of the IMC application. Also, a change of application state can trigger state transition of resource. State transition models for service, resource and application in IMC are shown in Fig. 8.

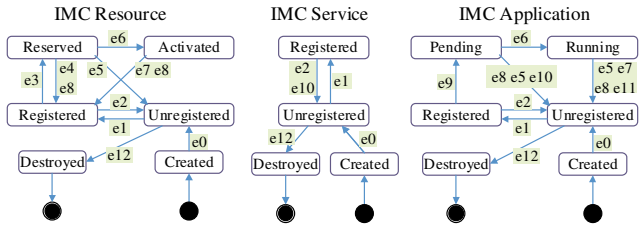


Fig. 8 State transition models of service, resource and application in an IMC. In the figure relevant evets are:
e0:add element, e1:register, e2:unregister, e3:reserve, e4:cancel reservation, e5:resource invalid, e6:resrouce available, e7:resource expired, e8:application invalid, e9:application start, e10:service invalid, e11:application terminated, e12:destroy element.

All state transition models in Fig. 8 start from creation. After adding an element to a working thread, the state of the element turns to unregistered and this state normally means related entities are not yet connected to the IMC. As for resource, if the application utilizing this resource becomes invalid, the resource state will transfer from reserved or activated to registered state, which means this resource is released back to the resource pool. A state transition model for service is much simpler since service instance can be shared by many applications at the same time which will save the "reserved state" from scheduling. The application state transition model is a little more complicated as it involves events from resources and services. Invalidation of resources or services will always cause the application to be unregistered, thus, when implementing the IMC architecture, only very serious errors or problems are allowed to generate the "invalid" event and in other situations try pending the application rather than unregistering it. Fig. 8 shows only very basic state transition models for IMC, however implementation of the IMC architecture will need more detailed models to handle more complicated situations.

To demonstrate the feasibility and advantages of the IMC

architecture brought forward by this paper, a practical system implemented upon this architecture is presented.

5 Implementation of the IMC Architecture

5.1 Coordination system and Message broker

The coordination system is used to record important configuration data and management data about resources, services and applications in the IMC. Here, Zookeeper, which is a distributed coordination system with fault tolerance ability, is utilized to store various data. Zookeeper uses a data structure called a Zookeeper path which is similar to the directory of a file system and where each node of a path can store data. Various message brokers can be used in the IMC and in this paper Rabbitmq is adopted.

5.2 VISA based IMC resource agent

First, to verify that the architecture is viable for instrument and sensor virtualization, a VISA (Virtual Instrument Software Architecture) based IMC resource agent is implemented. The agent uses an Apache Thrift RPC framework and all VISA driver interfaces are remotely mapped. Since Thrift supports cross language services development, it is also used as the service framework between all servers and clients in the IMC. Fig. 9 shows the details of the implemented IMC resource agent and how it interacts with the resource manager in the cloud.

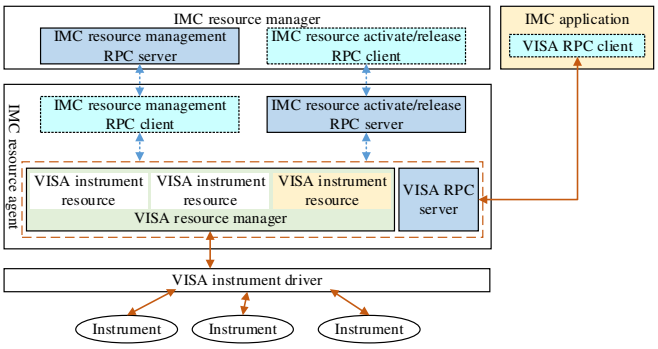


Fig. 9 Implementation of the IMC resource agent

As shown in Fig. 9, instrument resources are registered through resource management RPC services, which are implemented in the Thrift framework. To access the instrument resource, each IMC resource agent needs to run a VISA RPC server and it wraps all VISA driver interfaces. However, interfaces are extended to include a third parameter which is the access ID. Such access IDs contain both the name of the instrument resource and the reserved time span of the resource. The resource agent will also store a set of <access ID, instrument resource> maps and these maps are built up when applications in the cloud request the resources managed by this agent. Once the application in the IMC needs to control a resource, it will make a remote call with the access ID. On the agent side, the agent will get the corresponding resource through this ID and then call a local VISA instrument driver to control the instrument and then return the result to the application. To make the agent as independent with platforms as possible, pyvisa, which is a python implemented frontend of VISA driver, is used as the VISA resource manager. Although instruments and sensors are diverse in their hardware architectures and software interfaces, similar implementation can be applied to virtualize them into an IMC resource as long as their interfaces are available.

As for resources, the data structure used to record their information is shown in Fig. 10. When registering resources, the resource manager of the IMC manager will create a data path according to the domain, site and resource name. Here domain and site are used to constitute a two-level naming convention so that resource management can be more convenient and flexible. Whenever a reservation is made for a resource, a duration with a start and end time will be added as a child to the resource data path when the reservation becomes valid. And as long as a resource is registered, the IMC resource agent will listen on the data path for a child-adding event. If such an event happens, the agent will be activated.

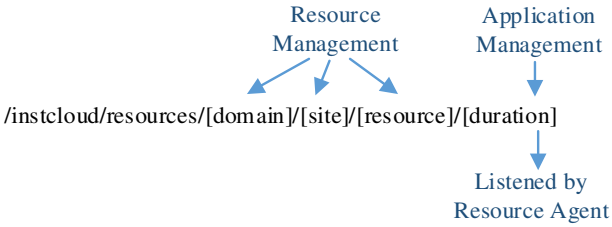


Fig. 10 Management data for IMC resource

5.3 Storm based IMC service for stream data processing

The next stage is for IM services to be implemented. As explained before, IM applications normally need to process real-time stream data, thus a stream data processing engine is required and related IM function modules need to be developed. In the work of this paper, Apache Storm[34] is used as the real-time streaming data processing engine. Storm is a distribute parallel stream data processing engine with fault tolerance whose maximum processing speed can reach around 1 million messages per second. Storm contains two types of components, which are Spout and Bolt. Spout is the data source and it can be connected to a message broker to subscribe message topics. Bolt is the process component. Spouts and Bolts compose a Topology which carries out the stream data processing logic. Each Spout or Bolt can run multiple instances so that they can process data in parallel. Topologies are wrapped into services, with certain Spouts functioning as input interfaces and some Bolts as output interfaces. Fig. 11 presents a simple example for computing electrical power to show how services in the IMC interact with applications and the IMC manager in the cloud.

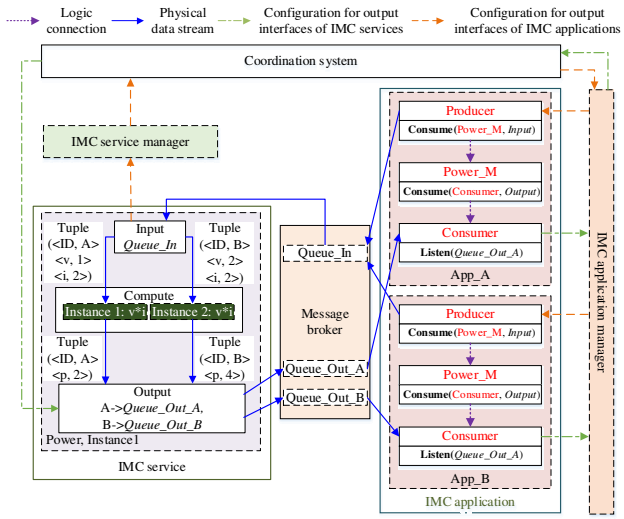


Fig. 11 A service implemented through Storm to compute electrical power

In Fig. 11, input interfaces of a service are implemented by instances of IMCSpout class, which is an extended Spout class with service management RPC clients. When a service is submitted, each IMCSpout instance will register the context of the message topic that this IMCSpout is listening on through those clients. Since Rabbitmq is used as the message broker, the detailed context of a message topic is wrapped into RMQContext class. To consume a service, an IMC application just needs to get the RMQContext instance of each input interface, create a Rabbitmq client corresponding to that context, and send data to the service input interface through that client.

Output interfaces are instances of an extended Bolt class named IMCBolt class with service management clients and they will also create management data entries in Zookeeper and listen on those data paths. However, it is the application manager that is responsible for writing message topic contexts to the paths. Whenever data on paths are updated, output interfaces of a service will update destination contexts and send output data to the corresponding message topic. Each context in an output interface is combined with a session ID and a module ID which will be introduced in the following part, and each message passed to an output interface will also contain these IDs. With these IDs, output interfaces will know which message topic the data should be sent to. Data paths for services are shown in Fig. 12.

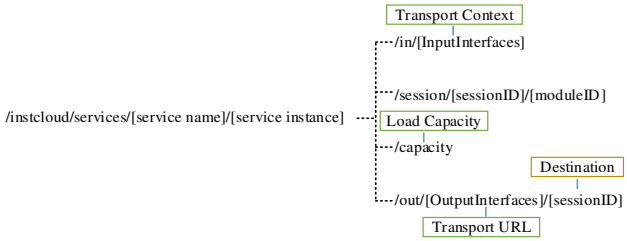


Fig. 12 Management data for IMC services

In Fig. 12, children under /in node are input interfaces of the service and similarly children under /out node are output interfaces. Each child node under /in node will store a Transport Context which records the context of the message topic that the interface is listening on. Each child node under /out will store a Transport URL which tells the output interface the message broker that is used to transmit data. Under each node of output interface there are child nodes representing IMC application sessions that consume output data from the output interface and each of the child nodes will store a Destination Object that records contexts of message topics for output data transmission.

The /session node under each topology instance or service instance node and its children are used for service state management. For example, when an IMC application session releases a service, the corresponding session ID and module ID will be deleted and such a deleting event will be listened on by the IMC service manager and related IMC service instance. Once such event happens, both the IMC service manager and related IMC service instance will clear data for that session.

The /capacity node stores load capacity of this service and the IMC manager will use this data for load balance and scaling.

5.4 IMC application developing mode and data routing mechanism in IMC

IMC applications are implemented through text programming language and currently only Java APIs (Application Programming Interfaces) have been developed. Four classes are defined according to entities in the IMC, which are ICResource, ICService, StreamProducer and StreamConsumer. ICResource and ICService are wrappers of the resources and services in the IMC. When creating ICResource objects, the domain, site, resource name and time span should be specified, but for ICService objects only service name is required. The ICResource class is normally wrapped with RPC interfaces that are used to control resources. StreamProducer is used to publish data to the input interfaces to a service while StreamConsumer is responsible for receiving data from the service. However, all related message broker contexts are automatically set when submitting the application. A complete IM process is wrapped into a session task and all related resources, services and other modules are managed through a Session object. All the four types of components in an IMC application session have their module IDs and each session has a universally unique ID, but the module ID is only unique to a session. Fig. 13 shows a diagram of a simple IMC application, which is also referred to in Fig. 11 for illustration.

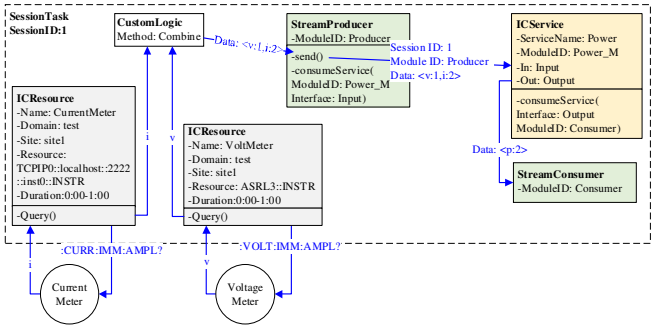


Fig. 13 An IMC application example

A code fragment for the IMC application in Fig. 13 is as follows.

ICResource voltMeterICRes = session.newICResource("test","site1", "ASRL3::INSTR", "VoltMeter");

ICResource currentMeterICRes=session.newICResource("test","site1", "TCPIP0::localhost:2222::inst0::INSTR", "CurrentMeter");

StreamConsumer strConsumer = session.newSink("Consumer");

StreamProducer strProducer = session.newHeader("Producer").consumeService("Power_M", "Input");

session.newICServiceModule("Power_M", "Power").consumeService("Output", "Consumer");

There is a consumeService method that is used to decide which module and interface the data of the current module should be sent to. For the StreamProducer module, the name of the next module and the interface should be provided, while for the service module the name of the service output interface and the next module and its input interface, if any, should be defined.

Data routing in IMC is relatively more complex than conventional IM programs. Fig. 14 shows how data are routed between multiple services.

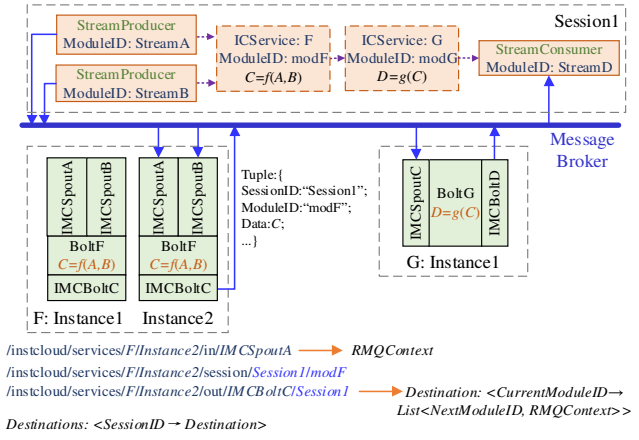


Fig. 14 Data routing in IMC

In Fig. 14 two services are consumed by the IMC application session, which is Session1. Here, simple IDs are used just for the convenience of illustration. StreamA and StreamB are instances of StreamProducer class. SteamD is an instance of StreamConsumer. IMCSpoutA, IMCSpoutB and IMCSpoutC are instances of the IMCSpout class while IMCBoltC and IMCBoltD are instances of IMCBolt. BoltF and BoltG are instances of the ordinary Bolt class.

When the IMC application manager processes service requests from an IMC application, it will assign an IMC service instance for each consumed service. In Fig. 14, IMC service F consumed by Session1 is assigned with IMC service instance2. The corresponding session ID (e.g. /Session1) and module ID (e.g. /modF) will be written into the data path of the IMC service instance (e.g. /F/Instance2/) for state management.

To send data from an IMC application session to an IMC service instance, the RMQContext object of each input interface should be returned to the IMC application session. For example, in Fig. 14, the RMQContext object stored on /IMCSpoutA will be returned to Session1 and the Rabbitmq client in StreamA will be configured according to that object. Similarly, StreamB will also be configured through the RMQContext object stored on the /IMCSpoutB node. In this way, data from Session1 can be transmitted into the correct input interfaces of each IMC service instance.

Once data are processed, e.g. calculated through function $f(x,y)$, results need to be output by output interfaces, e.g. IMCBoltC of Instance2. Since one IMC service instance can be shared by multiple IMC applications, to distinguish the source of each data, the session ID and related module ID should be attached to each data. For example, data sent from Session1 to Instance2 of IMC service F will be attached with session ID "Session1" and module ID "modF". As explained in Fig. 12, sessions that consume the output of an output interface of a service instance will create a child node under the data path of that interface. For example, in Fig. 14, node /Session1 is added to children of the /IMCBoltC node. This adding event will be listened on by IMCBoltC and a Map object named Destinations will be created in IMCBoltC to store destinations of data that are related to Session1. Detailed information about the destination will be stored as a Map object on the node of the session. For example, destinations for output data, which related to Session1, of IMCBoltC will be stored on the /IMCBoltC/Session1 node. Such destinations are organized as a Map object named Destination, and the key of the Map is the current module ID of the service (e.g. modF) and the value is a list of Object that stores the ID of the next module and RMQContext object of the next module's input interface. This Destination object will also be added to the Destination object in IMCBoltC. Now, with the session ID and the module ID attached to the data, IMCBoltC will know which message topics defined by RMQContexts in the list of Destination object the data should be sent to. A Destination object is also created and written to Zookeeper by the IMC application manager and this happens during the service request processing stage. In Session1, the output of IMC service F is connected to IMC service G, thus RMQContext of IMCSpoutC in Instance1 of IMC service G will be stored in the Destination object. And after finishing processing the service request from Session1, the whole Destination object of Session1 for service F instance2 will be written onto the /IMCBoltC/Session1 node. The reason why the ID of the next module is also recorded in the Destination object is that each data can only store the module ID of the current service instance

and, once data is passed to the next service instance, this module will be invalid. Thus before passing data to the next service instance, the value of the ModuleID field should also be updated to the ID of the next module. As in Fig. 14, "modF" will be replaced by "modG" in the date Tuple. Through the above data routing mechanism, data can be transmitted between different shared IMC services.

To send data back to an IMC application, the IMC application manager just needs to create a Destination object according to the RMQContext of an instance of StreamConsumer and write the object to the data path of output interfaces of the connected service instance. This process is similar to data routing between IMC services.

5.5 Implementation of IMC Manager

Implementation of IMC manager is shown in Fig. 15.

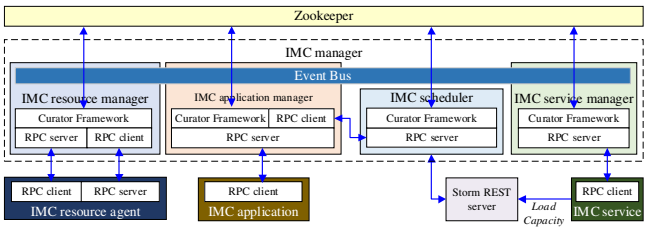


Fig. 15 Implementation of IMC manager

As shown in Fig. 15, the IMC manager needs to interact with Zookeeper, IMC resource agents, IMC applications and IMC services. In the implementation of this paper, Curator Framework is used to interact with Zookeeper. Most of the other remote management operations are carried out through the Apache Thrift RPC framework. To obtain load capacities of Storm-based services and schedule resources for those services, the IMC scheduler will call the Storm REST (Representational State Transfer) API. Each module of the IMC manager in Fig. 15 can run a thread pool for its RPC server, so that it can serve multiple RPC clients.

Currently, the IMC manager is implemented in a centralized way just to verify the feasibility and functionality of the IMC architecture in this paper. As shown in Fig. 15, the IMC resource manager, IMC service manager, IMC application manager and IMC scheduler are loosely coupled through an event bus. In this way, the IMC manager can manage the state of each IMC element according to Fig. 8. However, each module of the IMC manager is relatively independent, thus it will be very easy to implement the IMC manager in a distributed way, e.g. substitute event bus with message broker.

6 Application and Experiment

To test the designed IMC architecture, an application for power system state estimation (SE)[35] is developed based on the implemented system.

6.1 Distributed parallel power system state estimation

In a power system, not all states of the system are monitored and, even if some electric states are measured by instrumentation meters or sensors, the value may not reflect the true state due to measurement errors or bad data caused by disturbance to communication systems and many other factors. However, all real states of a power system should always obey the law of electric circuits. Thus, using these electric circuit laws and measured data, a group of measurement equations can be built up. With these equations, a mathematic model can be developed to estimate the true states of the whole power system. The most fundamental state estimation method is the WLS (Weighted least square) method[36], also referred to as the NE (Normal equation) method. And the mathematical model for the WLS method can be formulated through (1) to (4):

$$\mathbf{z} = \mathbf{h}(\mathbf{x}) + \mathbf{v} \tag{1}$$

Where $\mathbf{z}$ is the m dimension measurement vector, $\mathbf{x}$ is the $2n$-2 dimension state variable vector, $\mathbf{v}$ is the m dimension measurement error vector and $\mathbf{h}(\mathbf{x})$ is the relation function of measurements and the state variable $\mathbf{x}$.

$$\begin{cases} J(\mathbf{x}) = [\mathbf{z} - \mathbf{h}(\mathbf{x})]^{\mathrm{T}} \mathbf{W} [\mathbf{z} - \mathbf{h}(\mathbf{x})] \\ \mathbf{W} = \mathrm{diag}[\frac{1}{\sigma_1^2}, \cdots, \frac{1}{\sigma_i^2}, \cdots, \frac{1}{\sigma_m^2}] \end{cases} \tag{2}$$

Where $J(\mathbf{x})$ is the objective function, $\mathbf{W}$ is the $m \times m$ diagonal weight matrix, and σ_i^2 is the covariance of the ith measurement error.

$$\Delta\mathbf{z}(\mathbf{x}) = \mathbf{z} - \mathbf{h}(\mathbf{x}) \tag{3}$$

Where $\Delta\mathbf{z}(\mathbf{x})$ is the measurement residual vector.

$$\begin{cases} \mathbf{H}^{\mathbf{T}}(\mathbf{x})\mathbf{W}\mathbf{H}(\mathbf{x})\Delta\mathbf{x} = \mathbf{H}^{\mathbf{T}}(\mathbf{x})\mathbf{W}\Delta\mathbf{z}(\mathbf{x}) \\ \mathbf{H}(\mathbf{x}) = \frac{\partial \mathbf{h}(\mathbf{x})}{\partial \mathbf{x}} \end{cases} \tag{4}$$

Where $\mathbf{H}(\mathbf{x})$ is the Jacobian matrix of $\mathbf{h}(\mathbf{x})$ and $\Delta\mathbf{x}$ is the correction vector for estimated state variables.

The WLS state estimation method is carried out by iteration (4).

As there are bad data among measurements, a bad data recognition process is required to find and eliminate bad measurement data. A commonly used method is the normalized residual recognition method[37]. This method uses (5)-(6) to detect and identify bad measurement data.

$$\mathbf{r}_{\mathrm{N}} = \sqrt{\left(\mathbf{W} - \mathbf{H}(\mathbf{x})\left(\mathbf{H}^{\mathbf{T}}(\mathbf{x})\mathbf{W}^{-1}\mathbf{H}(\mathbf{x})\right)^{-1}\mathbf{H}^{\mathbf{T}}(\mathbf{x})\right)^{-1}} \Delta\mathbf{z}(\mathbf{x}) \tag{5}$$

Where $\mathbf{r}_{\mathrm{N}}$ is the normalized residual vector for measurement vector $\mathbf{z}$.

$$\gamma = \sqrt{\sum_{i=1}^{m} \sigma_i^2} \tag{6}$$

Where γ is the threshold for bad data recognition.

If the ith element $r_{\mathrm{N}i}$ of $\mathbf{r}_{\mathrm{N}}$ is greater than γ, then the corresponding measurement z_i is taken as the bad data suspect. And the measurement, which has the largest normalized residual larger than γ, is taken as the prime bad data suspect. Once bad measurement data are detected, they should be discarded and the state estimation process should restart. Normally, bad measurement data will not be discarded at one time, instead, only the bad data that has the prime suspect is discarded. The procedure of state estimation with bad data recognition for power systems is shown in Fig. 16.

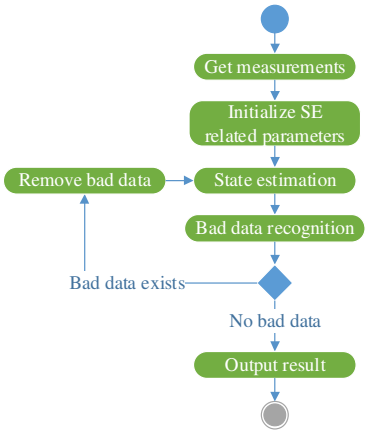


Fig. 16 Power system state estimation procedure

In Fig. 16 the state estimation step is actually carrying out the iteration process formulated in (4), while the bad data recognition step is calculating $\mathbf{r}_N$ and comparing its elements to γ.

Nevertheless, such an estimation process is quite computation-intensive and also consumes lots of memory, especially when the system is large. But still, the state estimation process is required to be as fast as possible. To achieve this goal, the parallel state estimation method[38] is introduced.

The parallel state estimation method is based on system partitioning. To implement a parallel state estimation algorithm, a large system should, firstly, be partitioned into several subsystems where all subsystems can estimate their own state in parallel. Each subsystem can use the aforementioned methods to estimate state except that the iteration process is different. In a parallel state estimation algorithm, after each iteration, all subsystems should share the states of boundary buses before the next iteration. The basic procedure of parallel state estimation algorithm is depicted in Fig. 17.

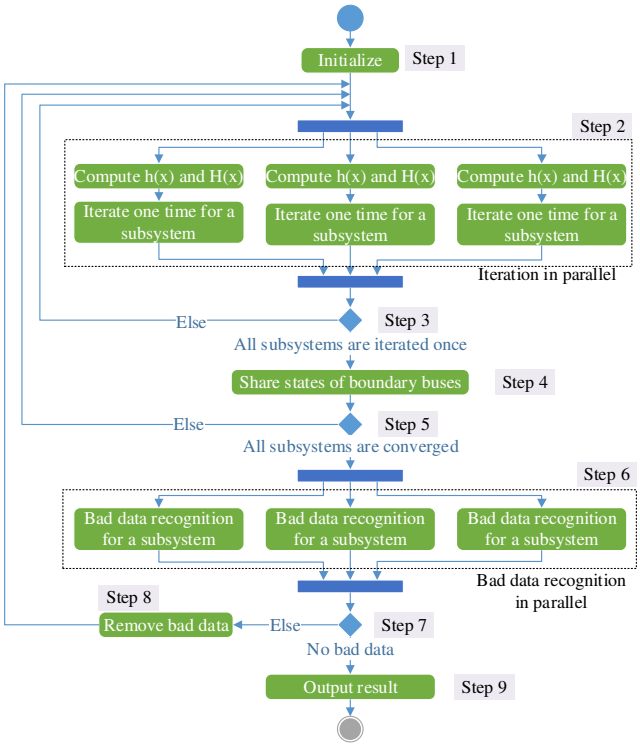


Fig. 17 Parallel state estimation for a large power system

In Fig. 17 iteration and bad data recognition tasks from multiple subsystems can be distributed in a cluster to accelerate the overall estimation speed.

6.2 IMC based power system state estimation

Since the IMC platform can greatly facilitate building distributed IM systems and provide efficient big data processing frameworks, this section tries to establish an IMC-based power system state estimation system. Such a system will not only make state estimation easier and more efficient, but can also test the functionalities that the IMC architecture brings up in this paper.

According to the IMC architecture elaborated on before, three aspects should be considered when developing an IMC-based state estimation system: (1) Virtualizing a measurement system into an IMC resource; (2) Implementing a parallel state estimation algorithm into an IMC service; (3) Developing a state estimation IMC application.

(1) Virtualizing a measurement system into an IMC resource

There are eight types of electric variables that need to be measured for state estimation. Since the test cannot be carried out in a real power system for safety reasons, all measurements are simulated by adding Gaussian noise to system power flow data.

As the implemented IMC resource agent is based on VISA, here, a meter that conforms to VISA is implemented for each system through a pyvisa-sim, which is an instrument simulation software for pyvisa, and custom defined instrument commands, such as ?MEA, are used to retrieve measurement data from the simulated meter. In this way, the measurement system of each power system can be virtualized into an IMC resource. However, in

practical applications, a corresponding IMC resource agent should be developed according to the physical measurement system.

Once a measurement system is virtualized into an IMC resource, a state estimation IMC application can retrieve all measured data by sending instrumentation commands through the RPC framework.

(2) Implementing a parallel state estimation algorithm into an IMC service

A parallel state estimation algorithm is implemented into an IMC service, which can be consumed by different state estimation IMC applications to estimate states of multiple power systems simultaneously. According to Fig. 17, a storm-based state estimation IMC service can be developed, as in Fig. 18.

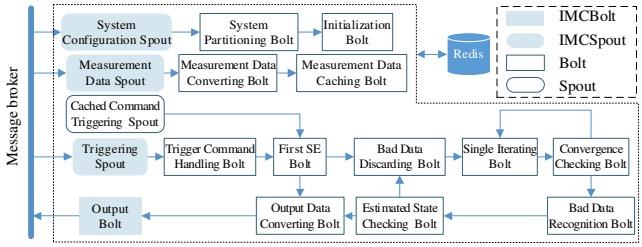


Fig. 18 Storm-based IMC service for power system estimation

The topology mainly contains three subsystems. The first is the system partitioning subsystem. This subsystem receives the configuration data of a power system from the SE IMC application through a System Configuring Spout. It is responsible for partitioning a large power system into small subsystems and initializing various parameters for SE. In this test, KaHIP[39], which is an effective and fast graph partitioning tool, is used to partition the power system. Also the topology is implemented through JAVA, however JAVA is not quite suitable for matrix computation, thus all matrix-related computations are carried out by Matlab. Partitioned data and initialized parameters are all stored in Redis[40], which is an in-memory database, so that computation processes can be separated from data, which is one of the rules for developing the IMC service. Redis uses a key-value data structure, and it is fast and very suitable for big data processing. As an IMC service is shared by multiple IMC applications, when caching data, a key should be attached to each data to identify its origin and that is why Redis is chosen as the caching database. Here, most of the intermediate data are cached in Redis.

The second subsystem is the measurement subsystem. It converts raw measurement data into formatted data, so that those data can be used for state estimation. Raw measurement data are acquired from the IMC resource corresponding to the virtualized measurement system of a power system by the SE IMC application, and then sent to the Measurement Data Spout through the message broker. A Measurement Data Converting Bolt will convert the data and then send the converted data to the Measurement Data Caching Bolt to store the data in Redis.

The third subsystem is the SE subsystem. This subsystem implements the parallel SE algorithm, as shown in Fig. 17. Whenever a power system needs to estimate state, it can just send a trigger command with the ID of the power system to the SE subsystem through the Triggering Spout. After receiving the trigger command, the Trigger Command Handling Bolt of the SE subsystem will check if the power system that requires SE is currently being estimated. If so, the SE subsystem will cache the command for the latter SE triggering, otherwise it forwards the command to the First SE Bolt. The Cached Command Triggering Spout will check all cached commands similar to the Command Handling Bolt periodically and send a valid command to the First SE Bolt. The First SE Bolt will then compute $J(\mathbf{x})$ and compare it to the corresponding threshold to see if the initial state is the estimated state. If $J(\mathbf{x})$ is below the threshold, the initial state is the estimated state and it will be forwarded to the Output Data Converting Bolt to convert the data for output, otherwise the SE trigger command will be sent to the Bad Data Discarding Bolt to start a new state estimation process.

The Single Iterating Bolt, the Convergence Checking Bolt, the Bad Data Recognition Bolt, the Estimated State Checking Bolt and the Bad Data Discarding Bolt implement step 2, steps 3-5, step 6, step 7 and step 8 in Fig. 17, respectively. However, there are three main differences. Firstly, the Bad Data Discarding Bolt has two inputs, which are the First SE Bolt and the Estimated State Checking Bolt. If the input is from the First SE Bolt, the Bad Data Discarding Bolt will do nothing but send the input command to the Single Iterating Bolt, otherwise it will discard bad measurement data and send a command to the Single Iterating Bolt for new SE. Secondly, as estimated states from each iteration are cached in Redis, all states will be updated immediately, which means states of boundary buses are shared in time by the Single Iterating Bolt and that is why no Bolt for step 4 in Fig. 17 is implemented. Thirdly, each of the Bolts in the SE subsystem can serve different power systems and do not bind to one specific power system. Such a loosely coupled processing characteristic is achieved by caching data in Redis and retrieving corresponding data of each power system through keys such as the ID of a power system. Once the state of a power system is estimated, it will be sent back to the corresponding SE IMC application through the Output Bolt. Parallel iteration and bad data estimation are implemented by running multiple instances of corresponding Bolts.

Once the SE topology is developed, it can be deployed into the IMC platform, and the SE IMC service can be started.

(3) Developing a state estimation IMC application

With the measurement system being virtualized and the SE IMC service running, to carry out state estimation, end users just need to develop a very simple SE IMC application to acquire measurement data of a power system from the corresponding IMC resource and send those data to the SE IMC service for SE online. Detailed activities of the SE IMC application are shown in Fig. 19.

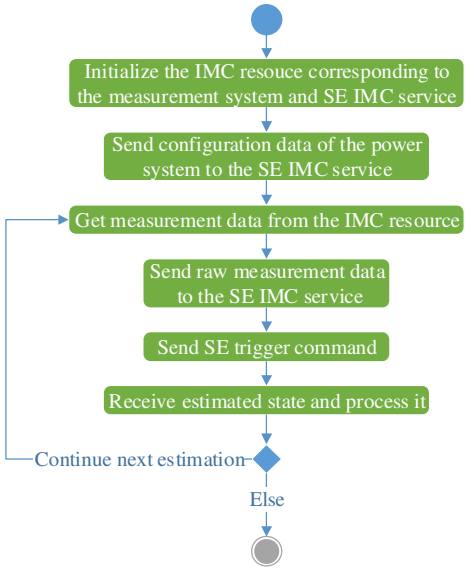


Fig. 19 Activity diagram of the SE IMC application

In Fig. 19 IMC resources and IMC services are defined through instances of ICResource Class and ICService Class respectively. Data are sent by instances of StreamProducer Class and are received by instances of StreamConsumer.

6.3 System deployment and test scenarios

The deployment of the whole IMC platform is shown in Fig. 20 with the whole system running on an Openstack IAAS cloud platform.

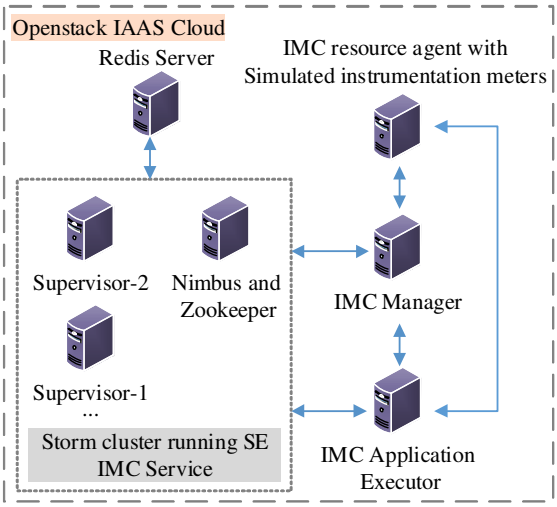


Fig. 20 Deployment of the whole system

Detailed configurations of nodes in the Openstack cloud and VMs of the IMC platform are shown in Table 1.

TABLE 1
CONFIGURATIONS OF NODES IN THE OPENSTACK CLOUD

Node type	CPU/Speed/ Quantity	Memory	Cores/ Threads
Control and network Node of the Openstack cloud	E3-1246/3.5GHz/1	16GB	4/8
Compute node of the Openstack cloud	E5-2620/3.2GHz/2	32GB	6/12
VMs for Supervisors of Storm cluster	E3-12XX/2.3GHz/1	8GB	4/4
VMs for Other nodes in the IMC platform	E3-12XX/2.3GHz/1	4GB	4/4

All hypervisors are connected by a Gigabit Ethernet switch.

In this test, case data from Matpower[41] are used and two test scenarios are set. In the first test scenario, state estimation for case3120sp is tested and the SE IMC service is exclusive to case3120sp. The number in the case name represents the number of buses in the system. This scenario is used to test the functionality of the implemented IMC platform so as to test the IMC architecture brought up in this paper. In the second test scenario, state estimations for case2869pegase, case3012wp and case3120sp are tested simultaneously and the SE IMC service is shared by multiple cases. This scenario is used to test the service sharing ability of the IMC architecture. Systems of these cases are very large in the electrical engineering field and, when running a parallel SE algorithm, each system is split into several subsystems. The number of buses in each subsystem is limited to 300 when splitting the system.

The most computation intensive Bolts are the Single Iterating Bolt and the Bad Data Recognition Bolt, and, while these two Bolts are under full load, all load capacities of other Bolts in Fig. 18 are less than 5%. Thus, multiple workers are set for the instances of these two Bolts. To find out which Bolt plays a more important role in determining the total estimation time T_{se}, a different number of workers are set for each of the Bolts.

6.4 Test results

The test result for the first test scenario is shown in Fig. 21.

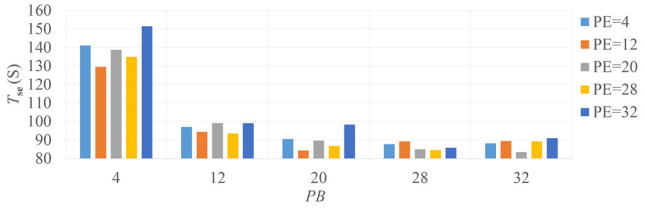


Fig. 21 State estimation time for case3120sp using the IMC platform

In Fig. 21, *PB* is the number of workers for the Bad Data Recognition Bolt and *PE* is the number of workers for the Single Iterating Bolt. Fig. 21 shows that, when increasing *PB*, estimation time will reduce dramatically. Fig. 21 also shows that, when *PB* is fixed, changing *PE* does not effectively influence the estimation time. However, when *PB* increases to 12 or larger, the estimation time does not decrease any more. This phenomenon is caused by the overheads from distributed computing, such as data transmission delay between computing nodes.

Fig. 21 demonstrates that the bad measurement recognition process is much more time-consuming than the estimation process. Fig. 21 also shows that sometimes

increasing *PB* or *PE* may cause performance degradation and that is because instances of Bolt may distribute across different computing nodes. When more directly-connected Bolt instances run on the same node, communication delay can be reduced. However, if more directly-connected Bolt instances distribute over different nodes, overheads from communication will degrade overall performance. Currently, the distribution of Bolt instances is carried out automatically by Storm and that is the reason for performance fluctuation in Fig. 21. Similar phenomenon will also happen in the second test scenario.

The result of the first test shows that the IMC architecture brought up in this paper is feasible and satisfies the basic functional requirements defined in section 3.

In the second scenario, the test results for each case is similar to Fig. 21, thus, those results are not presented. However, comparing the estimation time of case3120sp in the two different test scenarios is important, since it can reveal some characteristics of shared IMC services. Fig. 22 shows T_{se} of case3120sp in exclusive service mode and in shared service mode.

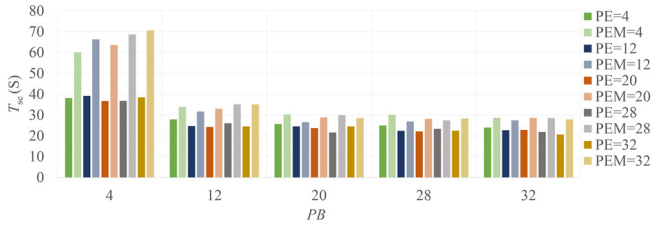


Fig. 22 Comparing T_{se} of case3120sp in exclusive service mode and in shared service mode

In Fig. 22, *PEM* designates the number of workers for the Iterating Bolt in the second test scenario. Fig. 22 shows that when *PB* is small, which means computing resource for SE service is inadequate, T_{se} is much higher in exclusive service mode than in shared service mode. However, when *PB* increases, T_{se} in exclusive service mode is only 10%-20% higher than in shared service mode. This demonstrates that, when computing resource is not strained, performance of the SE IMC service in shared service mode is very close to that in exclusive service mode, which means resource utilization efficiency can be greatly increased through service sharing in the IMC platform.

Such a resource utilization efficiency improvement is normally attributed to the overheads from synchronization of the parallel algorithm. For example, in the parallel SE algorithm shown in Fig. 17, step 2 or step 6 has to wait until all subsystems are processed to continue, and during this period some of the computing resource will be idle if the service implemented upon this parallel algorithm is exclusive. However, if the service is implemented in shared mode, the idle resource can be used for SE of other power systems, thus resource utilization efficiency can be improved.

Comparison of the results from the above two test scenarios demonstrates that the IMC architecture in this paper is viable for service sharing which can improve resource utilization efficiency.

7 Discussion

Although the IMC brought up in this paper can greatly facilitate utilization and management of IM resources, limitations and challenges still exist. Firstly, IMC is not suitable for those application scenarios that are highly time-critical and require extremely high reliability. Such limitation is caused by the latency and fluctuation of networks and overheads from message brokers, RPCs and distributed parallel computing frameworks. Secondly, high-speed and high-precision IM devices normally produce large amounts of data in a very short time, and directly transferring those large amounts of raw data in real time from IM devices to the IMC may be impossible due to the bandwidth limitation of the network. Thirdly, frequent remote procedure calls can bring a lot of overheads, especially for remote IM device control with short intervals.

Currently, a promising solution for the first and second challenges above is adopting fog computing[42] paradigms as a complementary framework between the IMC layer and the physical IM device layer. Fog computing is more focused on proximity to client objectives and end users, which leads to less latency and higher reliability. By pre-processing data locally or through fog computing, the amount of data that need to be transferred over the network can be greatly reduced, which will lower the requirement for the bandwidth of the network. And also, time-critical tasks can be carried out in a fog computing framework and other computation intensive tasks can be shifted to the IMC. In this way, the overall performance and QoS (Quality of Service) can be greatly improved.

To solve the third problem, frequent remote procedure calls can be substituted by direct interaction between local devices and the IMC services. RPCs can just be used to manipulate the interaction process rather than relay data between IM devices and the IMC.

8 Conclusion and Future Work

The instrumentation and measurement cloud can greatly facilitate management of instruments and sensors and at the same time allows users to utilize those resources and related IM services on demand remotely.

The IMC architecture brought forward in this paper provides efficient guidance for developing a practical IMC. With IM device virtualization and service wrapping, building a remote IM system just requires only very simple coding work. Most of the investment in IT facilities and system development work can be saved. Also with the ability to scale and load balance, the IMC can increase the utilization efficiency of various resources to a much higher level. Distributed parallel computing paradigms of the IMC will accelerate the processing speed, which brings lots of benefits for large-scale remote IM systems and also for analysis of big data coming from huge numbers of instruments and sensors. Application developed upon the implemented system has demonstrated the advantages of the work done in this paper.

However, more research work is still required to deal with some challenges. Such challenges include latency and stability of networks, geographic characteristics of the physical object that is being measured, and so on. These challenges are not proprietary to the IMC but common in the remote instrumentation and measurement field. But with more effort, problems caused by these challenges can eventually be solved.

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